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Laser structures with reduced dimensionality (beyond quantum wires) were first proposed to reduce threshold current and achieve wavelength tunability by Dingle and Henry in 1976, while Arakawa and Sakaki indicated potentially better temperature stability of a quantum dot (QD) laser. Here we review the latest developments in self-aligned QD lasers.

Self-organized quantum dots for optoelectronics

Emission at wavelengths of 1.3-1.7 μm can be achieved using InAs-GaAs QDs, and recent advances in growth have enabled GaAs 1.3 μm cw VCSELs with output power of about 0.7 mW and long operation lifetime.

Quantum dot (QD) lasers are of interest because of their potential to operate with low threshold current, low temperature sensitivity, and low chirp.

In particular, an overview of the formation of self-organized quantum dots (SOQDs) for optoelectronic applications was given at May's *Indium Phosphide and Related Materials* conference in Nara, Japan by N N Ledentsov and co-authors from TU Berlin and Ioffe Institute (St Petersburg, Russia) as well as the Air Force Institute of Technology (Wright-Patterson AFB). With SOQDs, thousands of QDs can be produced per second per square cm with good size and shape uniformity in an array without the need for lithography (yet still compatible with existing semiconductor processing technology). Also, by using ultra-dense arrays of very small QDs in wide-gap matrices, ultra-high modal gain can be achieved.

Emission at wavelengths of 1.3-1.7 μm can be achieved using InAs-GaAs QDs, and recent advances in growth have enabled GaAs 1.3 μm continuous-wave (cw) VCSELs with output power of about 0.7 mW and long operation lifetime.

Such QDs can be produced by the following different methods:

• three-dimensional (3D) QDs can be obtained by Stranski-Krastanow (SK) growth (with wetting layer, WL) or Volmer-Weber (VW) growth (without WL) in highly lattice-mismatched material systems like InAs-(Al)GaAs, GaSb-GaAs or InAs-Si.

Ultra-thin-layer (< 1 nm) AlAs overgrowth of small InAs QDs results in a replacement of In atoms of the WL with Al atoms, increasing the height and volume of the QDs. Ledentsov observed a reversibility of QD size, volume and density with substrate temperature ramping and/or cycling, demonstrating the thermodynmic nature of the self-limited island size growth mechanism. Temperature ramping experiments enable high-density, large-volume InAs-GaAs QDs emitting at 1.3 μm due to the In adatoms condensation at the islands. Even longer wavelengths could be obtained by growing vertically coupled InAs-AlGaAs QDs or laterally agglomerated InAs-GaAs QDs. SK and VW QDs enable low-threshold, high-cw-power GaAs-based lasers (N N Ledentsov *et al*, *IEEE J. Sel. Top. Quantum Electron.* 6, 439 (2000)). Carrier confinement in QDs may reduce facet heating and prevent current filamentation (key problems for high-power devices).

• ultra-dense (>10^{11} cm^{-2}) arrays of small (5-10 nm) and flat two-dimensional (2D) QDs can be formed by sub-monolayer (SML) deposition in InAs-GaAs and similar systems such as CdSe-ZnSe.

An increase in the substrate temperature causes shrinkage of the islands due to the higher concentration of adatoms (similarly for InGaN-GaN QDs formed by temperature-ramped growth). Vertically correlated or anti-correlated growth of QDs has been demonstrated for SML stacks (QDs formed by ultra-thin insertions are advantageous in wide-bandgap devices, as ultra-dense arrays of QDs may be formed). Resonant absorption coefficients up to 10^5 cm^{-1} and consequently gain coefficients may be realized. In addition, high-volume-density QD arrays may be used in low-finesse VCSELs (N N Ledentsov *et al*, *Thin Solid Films*, **367**, 40 (2000); I L Krestnikov, N N Ledentsov, A Hoffmann and D Bimberg, *phys. stat. sol.* (a) **183** (2), 207 (2001))

• GaAs QDs can be formed on a (311)A AlAs surface which is spontaneously nano-faceted with a period of 3.2 nm in the [0-11] direction and a corrugation height of 1 nm. When the surface is covered by less than 1 nm of GaAs, elongated GaAs clusters are formed in the AlAs grooves with a width of about 3 nm and a height of about 2 nm. For AlAs and GaAs layer thickness above 1 nm, arrays of quantum wires are formed. The interface corrugation is maintained after the AlAs overgrowth. Narrow luminescence (15 meV, corrugated superlattice with 3.7 nm period) is realized, indicating good uniformity. Arrays of isolated QWs or QDs may also be grown.

This approach is attractive for normal-incidence far-infrared (FIR) detectors, FIR emitters, three-terminal high-frequency lateral superlattice devices and polarization-stabilized VCSELs etc.

- QDs can be obtained by spinodal decomposition and activated spinodal decomposition in InGaAs-GaAs and InGaAsN-GaAs materials systems. When small coherent InAs islands are covered with an InGaAs alloy layer they act as stressors, attracting In adatoms and enabling growth of dense arrays of large and coherent QDs for 1.3 μm lasers (up to 3 W cw) (N N Ledentsov *et al*, *IEEE J. Sel. Top. Quantum Electron.* **6**, 439 (2000)).

1.3 μm quantum dot GaAs-based VCSELs

Lasers using self-organized QDs are particularly advantageous for VCSELs, as non-equilibrium carriers are localized in the QDs and thus spreading of non-equilibrium carriers out of the injection region can be suppressed. This may result in ultra-low threshold currents (< 70 μA) at ultra-small apertures (N N Ledentsov *et al*, *Semicond. Sci Technol.* **14**, 99 (1999)).

Milestones include:

- luminescence at 1.3 μm from InGaAs/GaAs QDs (Mukai *et al*, *Jpn J. Appl. Phys.* Part 2, 33 L1710 (1994));
- the first 1.3 μm QD lasers on GaAs substrates (D L Huffaker *et al*, *Appl. Phys. Lett.* **73**, 2564 (1998);
- high-power operation (M V Maximov *et al*, *Phys. Rev.* B **62**, 16671 (2000); A E Zhukov *et al*, *IEEE Photon. Techn. Lett.* **11**, 1345 (1999));
- single transverse mode operation (M V Maximov *et al*, *Electron. Lett.* **35**, 2038 (1999);
- the first 1.3 μm GaAs-based VCSEL (J A Lott *et al*, *Electron. Lett.* **36**, 1384 (2000));
- ultra-low threshold current density (16 A/cm^2) at room temperature (G T Liu, *IEEE J. Quantum Electron.* **36**, 1272 (2000)).

Other developments have been made by:

- CNET from 1985-1994 (the first proposal to use SK QDs for low-dimensional nanostructures; the first luminescence studies of vertically correlated growth, size uniformity and lateral ordering);
- UCSB (size uniformity);
- the University of Texas (first 1.3 μm GaAs-based QD laser);
- the University of New Mexico (ultra-low threshold current density QD lasers).

Now, J A Lott has reported 1.3 μm VCSELs with QD active regions suitable for microcavity applications (to be published), grown by solid-source MBE on (001) n$^+$ GaAs substrates. (1.3 μm VCSELs on GaAs substrates are of interest to replace both 850 nm GaAs VCSELs and InP edge-emitting lasers.)

The self-organized QDs consisted of planar sheets of initially small InAs pyramidal islands formed by a 2.5 monolayer InAs deposition covered by a 5 nm-thick $In_{0.15}Ga_{0.85}As$ layer. The QD sheets were separated by a 25 nm-thick GaAs barrier/ separation layer. Three-fold stacked QDs were used, with dot density per stack of 5×10^{10} cm^{-2}.

The microcavity was surrounded by (p) and (n) $Al_{0.98}Ga_{0.02}As$ layers (less than λ/4 thick) followed by 1λ-thick (p) and (n)GaAs current spreading/ intra-cavity contact spacer layers doped to 10^{18} cm^{-3}, followed by Distributed Bragg Reflectors (DBRs) composed of alternating $Al_{0.98}Ga_{0.02}As$ and λ/4-thick GaAs layers. The $Al_{0.98}Ga_{0.02}As$ layers in the DBR - as well as those surrounding the optical cavity - were selectively oxidized to form Al(Ga)O. The QDs were centred in a 1λ-thick Gas optical microcavity, whose edges were doped to 10^{17} cm^{-3}.

The threshold current was 1.2 mA, and was almost unchanged with temperature increase. The electroluminescence from QD LED test structures indicates that lasing proceeds via the QD ground-state transition. The maximum differential efficiency is 64%.

The emission wavelength was 1.28-1.306 μm, depending on the position on the wafer. Variation in threshold current across the wafer was about 10%. Lifetime testing over 700 hr cw at 35°C showed no change of performance.

Threshold current shows only weak dependence on aperture size down to sub-micron cavities, while the photon confinement effect becomes increasingly important.

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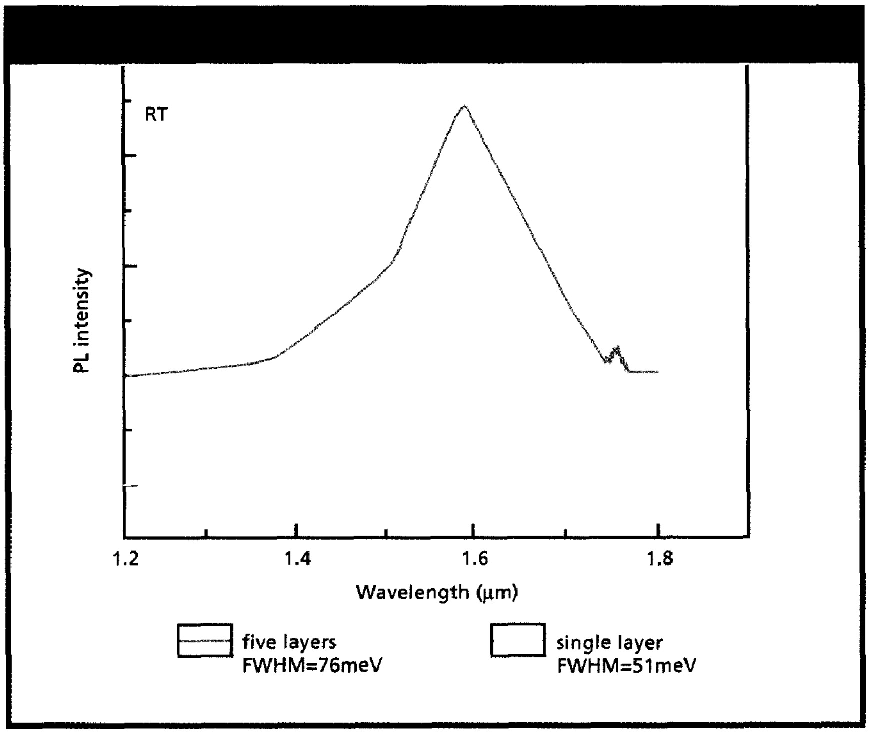

Figure 1. Room-temperature PL spectra of a single InAs QD layer and a five-period-stacked InAs QD layer in InAlGaAs matrixes (from NEC's System Device and Fundamental Research group).

Most recently, the Ioffe-TU Berlin work has included growing devices by MOCVD rather than MBE (R Sellin *et al*, *Appl. Phys. Lett.* 78 (9) 1207-9 (2001)).

1.55 μm InP-based QD lasers

Most quantum dot lasers have self-assembled InAs QD active layers on GaAs substrates, so the lasing wavelength is limited to a range from 1.0 μm (with large compressive stress due to the large mismatch with GaAs) to 1.3 μm (using an InGaAs layer). For lasing at 1.55 μm an InP substrate can be used. This gives few dislocations and high optical efficiency. However, at room temperature, optical gain is poor due to highly variable size and low density of the InAs QDs.

This is the first room-temperature ground-state lasing of a long-wavelength QD laser based on InP. Maximum modal gain of the ground state was estimated to be 20 cm^{-1} (twice that for QD lasers on GaAs substrates).

Saito, Nishi and Suou of NEC's System Device and Fundamental Research (Tsukuba, Japan) used MBE at 500°C to grow self-assembled uniformly sized InAs quantum dots with an InAl(Ga)As buffer layer on InP (311)B substrates with very high area density of 9×10^{10} cm^{-2} (compared to just 2×10^{10} cm^{-2} on (100)-oriented substrates, for which QDs were elongated along the [0-11] direction and PL was wider and less intense). These gave room-temperature PL at 1.5-1.6 μm. Average diameter was 30 nm and height 6.5 nm (±13%).

PL emission intensity and line-width showed little degradation as temperature was increased from 77-300K, indicating that carriers were confined strongly in the energy levels of QDs even at room temperature (see Figure 1).

InAs QD active layers with a 30 nm InAlGaAs capping layer were stacked in five-periods in a 470 nm $In_{0.52}Al_{0.29}Ga_{0.19}As$ separate confinement heterostructure (SCH) waveguide layer (since InAlAs gives too little optical confinement for lasing). A p-doped InP cladding layer and p-InGaAs contact layer were overgrown by MOCVD. A 2.08 μm x 50 μm stripe with 96% or 99% high-reflection-coated facet gave pulsed lasing at 1.63 μm (potentially useful for multi-wavelength amplifiers in DWDM fibre networks up to 1.6 μm) with a low threshold density of 380 A/cm^2 (the smallest for QDs on InP substrates, though greater than for QDs on GaAs substrates). *This is the first room-temperature ground-state lasing of a long-wavelength QD laser based on InP.* Maximum modal gain of the ground state was estimated to be 20 cm^{-1} (*twice that for QD lasers on GaAs substrates*).

In 1996 Osaka University's Institute of Scientific and Industrial Research reported high lateral density (10^{11} cm^{-2}) QDs self-formed by gas-source MBE growth in $(GaP)_n(InP)_m$ short-period superlattices (SLs) on GaAs (*N*11) substrates (S J Kim *et al*, *Jpn J. Appl. Phys.* 35 (1996) 4225). This was followed by reports in 1997 of current injection laser operation, in 1998 of lateral periodic variation of bandgap, and in 2001 of good optical properties. However, emission was at 0.62-0.67 μm.

J Mori *et al* have now reported high lateral density (10^{11} cm^{-2}) QDs self-formed by gas-source MBE growth at 480°C of five periods of $(GaAs)_2(InAs)_2$ short-period superlattices (with 10 nm-thick barrier layers of either InGaAs or InP) with a 150 nm-thick InP cap layer and 150 nm-thick InP buffer layer on InP (411)A substrates. The self-formed structures are produced by the strain-induced lateral composition modulation.

For InGaAs barriers, PL peaks were at 1.53 μm and 1.63 μm (the former from the InGaAs layers) with FWHM of 50 meV; for InP barriers there was a single peak at 1.45 μm with FWHM of 40 meV of strength 30 times that for InGaAs barriers.

Carrier confinement is enhanced by using InP layers as barriers. Since the effective bandgap energy of InP is higher than that of InGaAs, carrier overflow is suppressed, giving increased PL intensity and peak energy, so InP barriers were used consequently.

As superlattice period decreases, PL wavelength decreased due to the quantum size effect along the growth direction (vertical direction). PL wavelength can therefore be easily controlled from 1.3 to 1.6 μm.

Al-free 1.3 μm GaAs-based MBE-grown QD lasers

N T Yeh *et al* of National Central University, Taiwan last year showed that the relaxation of the strain in QDs is the key factor for long-wavelength emission (*Appl. Phys. Lett.* 76, 1567 (2000)). Also, significant blue shift occurs during annealing over 670°C, possibly due to inter-diffusion of In-Ga atoms between the InAs QDs and GaAs barriers (T M Hsu *et al*, *Appl. Phys. Lett.* 76, 691 (2000)).

To avoid blue shift due to high-temperature growth of the upper AlGaAs cladding layer, low substrate temperature of about 600°C is usually used. However, this makes high optical quality AlGaAs cladding layers hard to obtain.

Now Yeh *et al* have grown InAs/GaAs QD step SCH lasers with a 300 nm GaAs buffer by solid-source MBE at 580°C on (100) GaAs substrates with InGaP cladding layers at 500°C (using the normal 0.1 ML/s InAs growth rate rather than the very low growth rate of Huffaker and Zhukov, and 1 μm/hr for the GaAs and InGaP layer).

The 200 nm-thick active region (sandwiched between undoped 70 nm-thick GaAs barrier layers and 1.5 μm-thick n- and p-type InGaP cladding layers with doping concentrations of $5x10^{17}$ cm^{-3} grown at 490°C) consisted of three stacks of 2.7 ML InAs QDs covered with 6 nm $In_{0.16}Ga_{0.84}As$ strain-reducing layers separated by 30 nm undoped GaAs spacers grown at 520°C. This could extend the emission wavelength up to 1.3 μm at room temperature.

Such aluminium-free 50 μm-wide ridge waveguide lasers gave room-temperature PL with a FWHM of 21 meV and ground-state emission at 1300 nm (compared to 34 meV and 1320 nm for AlGaAs-clad QD lasers grown at a low temperature of 620°C fabricated for comparison - see Figure 2).

The blue shift could be due to the hydrostatic compressive strain in InAs QDs. The InGaP cladding layer is lattice matched to GaAs within 90 ppm, compared to a tensile strain of 580 ppm for the AlGaAs which leads to a lower compressive strain in the QDs and longer emission wavelength with AlGaAs.

As-cleaved InGaP-clad lasers with a cavity length of 4.2 mm lased at 1.2 μm with a room-temperature threshold current density of 138 A/cm^2, internal quantum efficiency of 31%, and an internal loss of 1.35 cm^{-1}. This is an order of magnitude less than InP-based QW lasers (perhaps due to the lower absorption loss of QDs and less free carrier absorption by the low-doping cladding layers). By comparison, no stimulated emission is observed from the AlGaAs-clad lasers unless high-reflection coating is applied to the facets, implying higher optical loss.

From 20-150K the lasing wavelength is weakly dependent on temperature and is associated with the ground state, but from 160-300K a red shift with increasing temperature is associated with the 1st excited state.

Likewise, below 230K threshold current density is a low 30 A/cm^2 and characteristic temperature T_0 a high 425K, but above 240K T_0 decreases dramatically to 55K.

GaInNAs/GaAs QDs by CBE

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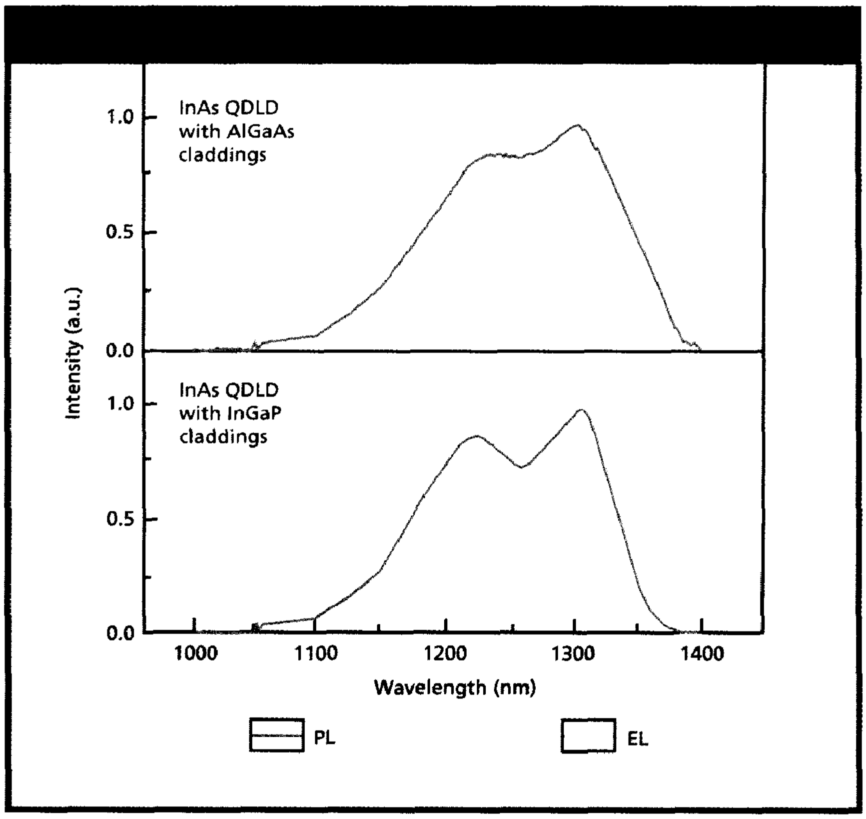

Figure 2. Photoluminescence and electroluminescence spectra for InAs QD lasers with AlGaAs and InGaP cladding layers (N T Yeh et al, National Central University, Taiwan).

For GaInNAs QDs the size increased from 30 to 40 nm while the density remains high. This suggests the possibility of controlling the size while independently keeping the density high, so the emission wavelength may be controlled by N incorporation.

However, compared to QW lasers, 1.3 μm QD VCSELs still suffer from an increase in threshold current at high temperature and low gain. It is difficult to increase the QD density while keeping the emission wavelength long because of the trade-off relation of growth characteristics between the dot density and the dot size.

But the wavelength can be extended by incorporating nitrogen, since it reduces the bandgap energy due to the large bandgap bowing parameter of III-V-N dilute nitride compounds. Growth of GaInNAs QDs by gas-source MBE and chemical beam epitaxy (CBE) has been reported (M Sopanen *et al*, *Appl. Phys. Lett.* **76** (2000) 994; S Makino *et al*, *J. Crystal Growth* **221** (2000) 561). Makino *et al* investigated the increase of dot density by introducing 1% of N.

Now, Shigeki Makino *et al* of the Tokyo Institute of Technology's Microsystem Research Center has grown $Ga_{0.29}In_{0.70}N_{0.01}As/GaAs$ QDs by CBE from 450-540°C at 0.1 ML/s. Compared to InGaAs QDs grown at 530°C of lateral dot size 47 nm and dot density $3x10^{10}$ cm^{-2}, introducing 1% of N to produce GaInNAs QDs at 540°C reduced the size to 38 nm and increased density to $9x10^{10}$ cm^{-2}. For InGaAs, increasing the growth temperature or decreasing the growth rate increased the dot size and decreased the density due to the increase of migration length. So, in GaInNAs, the N atom may change the surface potential due to its strong bond, decreasing the migration length on the surface.

Also, since 3D S-K growth reduces the strain energy, increased local strain around N atoms (due to a large difference of atomic radius between other atoms) may change the growth mode from 2D to 3D. Assuming a hexagonal close-packed QD structure for InGaAs QDs, as the growth temperature increased so the density decreased and the distance between neighbouring QDs increased with increasing lateral size; but for GaInNAs QDs the size increased from 30 nm to 40 nm while the density remains high. This suggests the possibility of controlling the size while independently keeping the density high, so the emission wavelength may be controlled by N incorporation.